Observation of the Charged Hadron $Z_c^{\pm}(3900)$ at $\sqrt{s} = 4170$ MeV

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The BES III Collaboration has reported observation of a resonance, which they call $Z_c(3900)$, which decays into J/ψ + a charged pion. This charged state was observed as an intermediate resonance in their analysis of e^+e^- annihilations into $J/\psi + \pi^+\pi^-$ at $\sqrt{s} = 4260$ MeV, the peak of the vector state Y(4260). We observe this charged state, $Z_c^{\pm}(3900)$, at a 6σ significance level in the analysis of 586 pb^{-1} of data taken with the CLEO-c detector at $\psi(4160)$. Our results, $M(Z^{\pm}) = 3885 \pm 5(\text{stat}) \pm 1(\text{syst})$ MeV, $\Gamma(Z_c^{\pm}) = 34 \pm 12(\text{stat}) \pm 4(\text{syst})$ MeV, and $R = \sigma(e^+e^- \to \pi^{\mp} Z_c^{\pm}(3900))/\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = (35 \pm 11)\%$ are in good agreement with those reported by BES III. We also present evidence for the observation of the neutral $Z_c^0(3900)$ at a 3σ level of significance with parameters in agreement with those of $Z_c^{\pm}(3900)$. Because our observations are made at the peak of the 2^3D_1 state of charmonium, we do not find any reason to attribute any unconventional properties to the initial state formed by the e^+e^- annihilations.

In a recent posting in the archive [1], BES III has reported observation of a charged hadron $Z_c(3900)$ with mass 3900 MeV, and width $\sim$ 46 MeV, which decays into a charged pion and J/ψ. This is an important finding because a charged hadron decaying into a charmonium state plus a charged meson must contain at least four quarks. If confirmed, this observation would herald the possible existence of a family of other charged states in this mass region. Several charged hadrons were reported earlier by Belle; in the charmonium region $Z_c(4050, 4250)$ [2], and $Z_c(4430)$ [3], and in the bottomonium region, $Z_b(10610, 10650)$ [4]. So far, these states have not been independently confirmed, and many remain controversial.

The BES observation of Z_c was made in e^+e^- annihilation at the vector resonance Y(4260), which is known to have unusual characteristics and does not fit in the conventional spectrum of charmonium states. Clearly, it is very important to confirm the existence of $Z_c(3900)$, and to also determine if it is populated in e^+e^- annihilation at a resonance which has well established charmonium credentials. We have made a search for Z_c in the same decay chain as BES

$$e^+e^- \to \pi^{\mp} Z_c^{\pm}, \quad Z_c^{\pm} \to \pi^{\pm} J/\psi,$$

but using CLEO-c data taken at $\sqrt{s} = 4170$ MeV, on the peak of the well-known $\psi(4160)$ charmonium resonance.

We use 586 pb^{-1} of e^+e^- collision data taken at $\sqrt{s} = 4170$ MeV at the CESR collider at the Cornell University, with final state particles detected and identified in the CLEO-c detector. The CLEO-c detector has been described in detail elsewhere [5].

We make the event selection for $\psi(4160) \to \pi^+\pi^- J/\psi$, $J/\psi \to e^+e^-, \mu^+\mu^-$, as in our paper [6] on the search for charmonium-like exotic mesons in the radiative decay of $\psi(4160)$, except that we do not allow any photons. To reconstruct the $\pi^+\pi^- J/\psi$ final state, we select events with 4 charged particle tracks with zero net charge. Tracks are reconstructed in the region with $|\cos\theta_{tr}| < 0.93$, where θ is the polar angle, and are required to be well-measured and consistent with originating at the interaction point.

Charged particle tracks are first identified on the basis of their momenta. Leptons (e, μ) from the decay of J/ψ have momenta $>$ 1 GeV, and pions have momenta $<$ 1 GeV, which makes π/μ separation easy. Pion candidates are additionally required to have an energy loss in the drift chamber (dE/dx) consistent with that expected for pions within 3σ.

Muons are distinguished from the electrons based on the variable E_{CC}/p, where p is the track momentum measured in the drift chamber and E_{CC} is the energy deposited in the calorimeter associated with the charged particle track. This variable clearly separates electrons, which deposit all of their energy in the calorimeter and have $E_{CC}/p \approx 1$, from muons which pass through the calorimeter and deposit only minimum ionizing energy. Muons are required to have $E_{CC}/p < 0.25$. To reject backgrounds from photon conversions, we require $\cos(\pi^+, \pi^-) < 0.98$ and $\cos(\pi^{\pm}, e^{\mp}) < 0.98$.

To select fully reconstructed events and improve mass resolution, a 4C kinematic fit is performed constraining the $\pi^+\pi^- J/\psi$ final state to a common vertex with $\chi^2_{\text{vertex}} < 20$, and the e^+e^- collision energy and momentum with $\chi^2_{\text{4C fit}} < 20$. In the following, we use the momenta of the charged particles after the kinematic fit. To select events containing a $J/\psi \to e^+e^-, \mu^+\mu^-$ decay, we select events with a $e^+e^-/\mu^+\mu^-$ mass consistent with that of the J/ψ within $\pm 20\,\text{MeV}/c^2$.

The observed J/ψ decays are illustrated in Fig. 1. For the the well defined peaks of J/ψ we obtain for $\mu^+\mu^-$ decay, $M(J/\psi) = 3096.5 \pm 0.5$ MeV, $N = 137 \pm 15$ counts and a fitted resolution width of 4.2 ± 0.5 MeV, and for e^+e^- decay $M(J/\psi) = 3096.3 \pm 0.5$ MeV, $N = 96 \pm 11$ counts and a fitted width of 3.9 ± 0.5 MeV. Monte Carlo determined efficiencies for decays containing $\mu^{\pm}$ are $\epsilon = 51\%$, and for decays containing $e^{\pm}$ are $\epsilon = 43\%$. We estimate the radiative correction factor $C = 0.82$. The cross sections are determined as $\sigma(e^+e^- \to \pi^+\pi^- J/\psi) =$

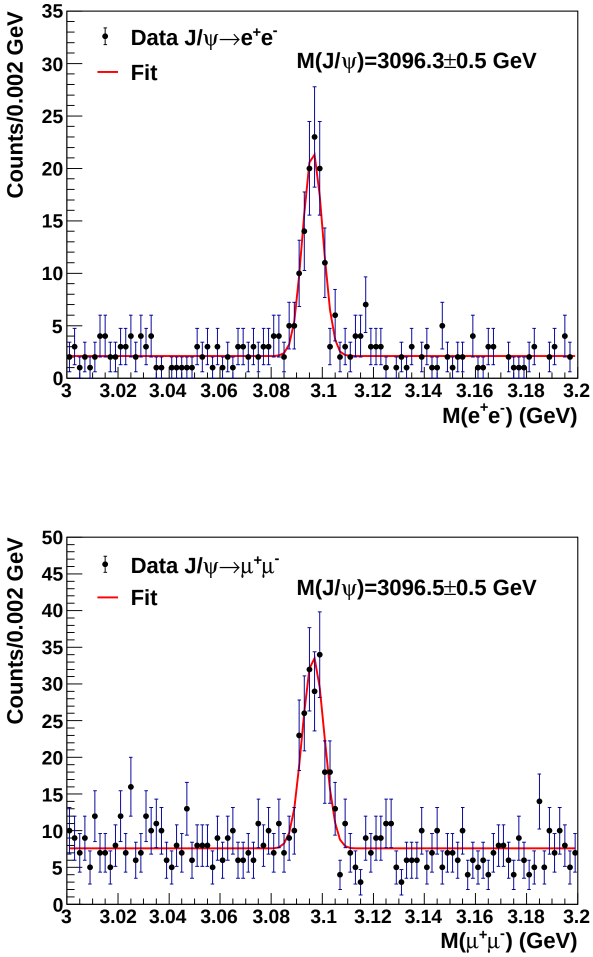

FIG. 1. Invariant mass distributions for $J/\psi \to e^+e^-$ (top) and $J/\psi \to \mu^+\mu^-$ (bottom) events. The curves show results of fits with gaussian peaks and constant background. The PDG average $M(J/\psi) = 3096.916 \pm 0.011$ MeV [8].

$N/\mathcal{L}\,\epsilon\,C$. They are $\sigma = 9.5 \pm 1.0$ pb ($\mu^\pm$), and $\sigma = 7.9 \pm 0.9$ pb ($e^\pm$), with the average value of 8.6 ± 0.7(stat) pb. This is nearly 1/7 th of the cross section observed by BES in decays from Y(4260).

We construct distributions of the maximum of $M(\pi^+ J/\psi)$ and $M(\pi^- J/\psi)$, labeled $M_{\max}(\pi^\pm J/\psi)$, the same observable as BES, in two regions defined as the J/ψ resonance region, $M(e^+e^-, \mu^+\mu^-) = 3097{\pm}20$ MeV, and the sideband regions, $M(e^+e-, \mu^+\mu^-) = 3030 \pm 30$ MeV and $M(e^+e-, \mu^+\mu^-) = 3170 \pm 30$ MeV. We find that there is no peaking in the distribution for the sidebands, and that its shape is identical within statistical uncertainties with the shape of the phase space distribution. Fig. 2 shows the $M_{\max}(\pi^\pm J/\psi)$ distribuion for the resonance region. The enhancement at ~ 3880 MeV, which we attribute to the Z_c resonance, is clearly visible.

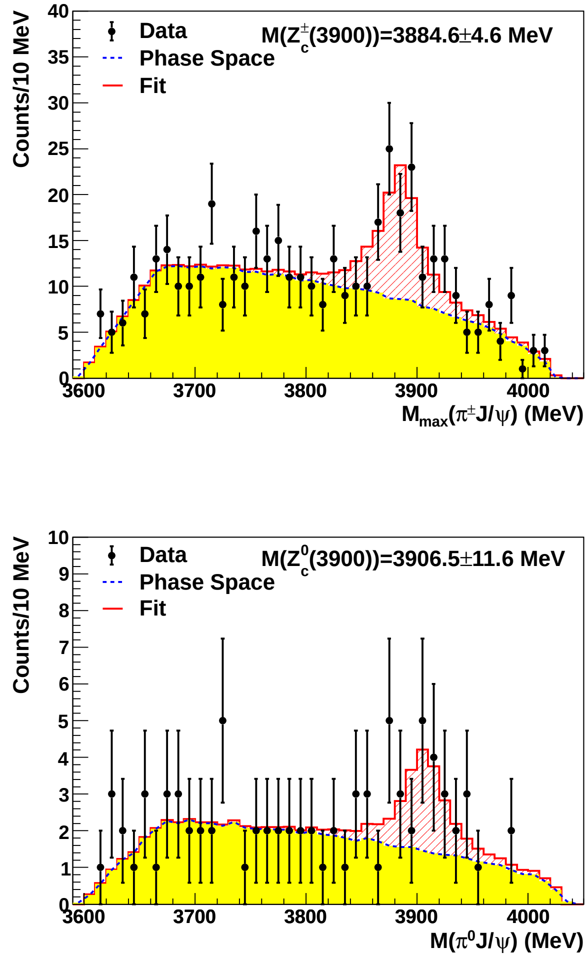

FIG. 2. Distribution of $M_{\max}(\pi^{\pm,0} J/\psi)$, as observed in the decays (top) $\psi(4160) \to \pi^+\pi^- J/\psi$ and (bottom) $\psi(4160) \to \pi^0\pi^0 J/\psi$. The points with errors bars are data. The histogram shows the results of the fit with the hashed part showing the Breit-Wigner function convolved with a gaussian resolution function for the Z_c resonance, and the shaded part showing the MC-determined shape for phase-space $J/\psi\pi\pi$ decays.

The distribution was fitted assuming the phase space MC shape for the background and a peak whose shape was obtained by convolving the MC determined instrumental width of 3.8 MeV with a Breit-Wigner resonance. The normalization of the background, the position of the peak, its width, and its magnitude were kept free in the fit. The result of the fit was number of counts, $N = 81 \pm 20$, mass $M(Z_c) = 3885 \pm 5$(stat) MeV, and width $\Gamma(Z_c) = 34 \pm 12$(stat) MeV. The $\chi^2/d.o.f.$ of the fit is 35/37. The likelihood-determined significance of the peak is 6.1σ.

We evaluate systematic uncertainties as follows. Our fitted J/ψ masses differ from the known $M(J/\psi) =$

TABLE I. Summary of fit results and comparison with results from BES III [1].

		$\sqrt{s}$ GeV	$\mathcal{L}$ pb^{-1}	$N(J/\psi \to \mu^+\mu^-/e^+e^-)$	$\sigma(e^+e^- \to \pi\pi J/\psi)$, pb	$N(Z_c)$	signif. σ	$M(Z_c)$ MeV	$\Gamma(Z_c)$ MeV	R %
BES III	$\pi^+\pi^-$	4.26	525	$882 \pm 33/595 \pm 28$	62.9 ± 1.9	307 ± 48	> 8	3899 ± 6	46 ± 22	22 ± 3
Present	$\pi^+\pi^-$	4.17	586	$137 \pm 15/\ 96 \pm 11$	8.6 ± 0.7	81 ± 20	6	3885 ± 5	34 ± 13	35 ± 11
	$\pi^0\pi^0$	4.17	586	$40 \pm 8/\ \ 29 \pm 5$	5.7 ± 0.8	17 ± 10	3	3907 ± 12	34 ± 29	25 ± 15

3096.916 ± 0.011 MeV by less than 0.5 MeV, which implies that the systematic uncertainty in our mass calibration is less than 0.5 MeV. To estimate the uncertainties due to the choice of the phase space shape for the background, we consider the background shape used by BES, $a/(x-3.6)^b + c + dx$ [1]. An equally good fit is obtained with $\chi^2/d.o.f. = 33/34$. This leads to systematic uncertainties of ± 0.2 MeV in mass, ± 4 MeV in width, and $\pm 17\%$ in cross section. We estimate the uncertainty in the MC-determined resolution width by varying it by $\pm 10\%$; it leads to systematic uncertainties of $< \pm 0.1$ MeV in mass, ± 0.5 MeV in width, and $< 1\%$ in cross section. We estimate the systematic uncertainties due to track reconstruction to be 1% per track. We estimate a 1% uncertainty due to the luminosity measurement [7]. The branching fractions for $J/\psi \to e^+e^-, \mu^+\mu^-$ have an uncertainty of 1% [8]. In quadrature, all these add to a systematic uncertainty of ± 1 MeV in mass, ± 4 MeV in width, and 18% in the cross section.

As Table I shows, our final results, including systematic uncertainties are $M(Z_c) = 3885 \pm 5$ MeV and $\Gamma(Z_c) = 34 \pm 13$ MeV. These are in good agreement with those reported by BES, $M(Z_c) = 3899 \pm 6$ MeV, and $\Gamma(Z_c) = 46 \pm 22$ MeV [1]. We obtain the ratio

$$R = \sigma(e^+e^- \to \pi^\mp Z_c^\pm(3900))/\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = (35 \pm 11)\%,$$

which is also in good agreement with $R = (21.5 \pm 3.3)\%$ reported by BES [1].

The $Z_c^\pm$ state decaying into $J/\psi\pi^\pm$ has isospin $I = 1$. If the pion is in the S–state, with respect to J/ψ, $J^{PC}(Z_c) = 1^{+-}$, which is not allowed for a $q\bar{q}$ meson. As has been noted by Maiani et al. [9], it is interesting to look for the neutral member of this "exotic" isospin triplet in the decay to $\pi^0\pi^0 J/\psi$. Taking account of isospin and the nearly factor two smaller efficiency for detecting $\pi^0\pi^0$ compared to $\pi^+\pi^-$, we expect to observe only ~ 60 $J/\psi\pi^0\pi^0$ events, and ~ 20 Z_c^0. Despite the limited expected statistics, we have made this measurement. The observed distribution of $J/\psi\pi^0$ events is shown in Fig. 3. The distribution is fitted in exactly the same manner as in Fig. 2. The results are $N(Z_c^0) = 17 \pm 10$ counts, $M(Z_c^0) = 3907 \pm 12$ MeV, $\Gamma(Z_c^0) = 34 \pm 29$ MeV, and $R = (25 \pm 15)\%$. The likelihood determined significance of the Z_c^0 peak is 3σ. These results are also listed in Table 1, and are in agreement with those for $Z_c^\pm$ within their statistical errors.

To summarize, our observations provide independent confirmation of the existence of the $Z_c^\pm(3900)$ state, and provide new evidence for the existence of the neutral member $Z_c^0(3900)$ of this isospin triplet. It is important to note that our observations of $Z_c^{\pm,0}(3900)$ are based on e^+e^- annihilations at $\sqrt{s} = 4170$ MeV, on the peak of the well-established 2^3D_1 vector state of charmonium, and therefore we do not need to attribute any unconventional properties to the initial state, as may be invoked for the observation of $Z_c^\pm$ at $\Upsilon(4260)$.

This investigation was done using CLEO-c data, and as members of the former CLEO Collaboration we thank it for this privilege. This research was supported by the U.S. Department of Energy.

Note added—As we were preparing to submit this paper, we became aware of a paper from the Belle Collaboration that also reports on the $Z_c^\pm(3900)$ from $\Upsilon(4260)$ [10].

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